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(54) **Title:** PLASMA ENHANCED CATALYTIC CONVERSION METHOD AND APPARATUS

(57) **Abstract:** A method of facilitating a chemical reaction, the method comprising: generating a plasma by introducing a plasma source gas as a vorticular or swirled flow into microwave radiation contained in a non-resonant multimodal microwave cavity. The method further comprising: directing the plasma into contact with a catalyst; directing a plurality of reagents into contact with the catalyst; and performing at least some of the method steps at a pressure greater than atmospheric pressure (101,325 Pa). The method further comprises controlling a flow of each of the plurality of reagents independently. Also, an apparatus for facilitating a chemical reaction in accordance with the method.

## Plasma enhanced catalytic conversion method and apparatus

### Technical Field

5 A method and apparatus for enhanced catalytic conversion.

### Background

10 Plasma enhanced catalytic conversion may be used in the field of chemical production, potentially in a continuous manner and in large quantities. It may be particularly appropriate for converting a by-product of a previous chemical process in order to produce a product of higher value. Furthermore, the plasma enhanced catalytic conversion may require lower energy than prior art techniques for producing the same end product.

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Examples of chemicals that might be produced using the subject method and apparatus include fuels such as branched and straight chain hydrocarbons, syngas (a combination of carbon monoxide, CO, and hydrogen H<sub>2</sub>), methanol (CH<sub>3</sub>OH) and formaldehyde (CH<sub>2</sub>O, HCHO). In such cases, starting materials include methane (CH<sub>4</sub>) and carbon dioxide  
20 (CO<sub>2</sub>). A further example of a chemical that might be produced using the subject method and apparatus is ammonia (NH<sub>3</sub>). Starting materials for such a product may be nitrogen (N<sub>2</sub>) and hydrogen (H<sub>2</sub>). A further example of a chemical that might be produced using the subject method and apparatus is nitric oxide (NO). Starting materials for producing nitric oxide (NO) may be N<sub>2</sub> and O<sub>2</sub>. (Nitric acid (HNO<sub>3</sub>) can be derived from nitric oxide (NO)  
25 first by oxidising the nitric oxide (NO) to form nitrogen dioxide (NO<sub>2</sub>) and then reacting it with water (H<sub>2</sub>O) to produce nitric acid (HNO<sub>3</sub>)).

Prior art methods for the conversion of methane to fuels are generally indirect and involve processes such as steam reforming. Such processes generally require significant energy  
30 input and are inefficient.

Prior art production of ammonia (NH<sub>3</sub>) is generally achieved using the Haber process that relies on high pressure (of the order of 100 standard atmospheres (10 MPa)) and high temperature (of the order of 450 °C) to form anhydrous liquid ammonia (NH<sub>3</sub>).

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Prior art production of nitric oxide (NO) avoids the direct oxidising of nitrogen (N<sub>2</sub>) since the energy required to enable this reaction is very high. Instead, prior art production of nitric oxide (NO) generally involves catalytic combustion of ammonia (NH<sub>3</sub>) by air in the presence of platinum and rhodium catalyst. This reaction requires a pressure of 9 atmospheres  
5 (911,925 Pa) and 900 °C.

GB 2442990 discloses a microwave plasma apparatus with vorticular gas flow that operates at relatively low temperatures and pressures and which may be applicable to the method and apparatus of the present disclosure.  
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### Summary of the disclosure

Against this background, in a first aspect of the invention there is provided a method of  
15 facilitating a chemical reaction, the method comprising:

generating a plasma by introducing a plasma source gas as a vorticular or swirled flow into microwave radiation contained in a non-resonant multimodal microwave cavity;  
directing the plasma into contact with a catalyst;  
directing a plurality of reagents into contact with the catalyst; and  
20 performing at least some of the method steps at a pressure greater than atmospheric pressure (101,325 Pa),  
wherein the method comprises controlling a flow of each of the plurality of reagents independently.

25 Advantageously, the method provides an energy efficient chemical conversion at relatively low temperature and pressure. In using the technique for the production of fuels, for example, partial oxidation of methane (CH<sub>4</sub>) can take place directly by mixing with carbon dioxide (CO<sub>2</sub>) (itself a by-product from energy intensive industrial processes), reduction of carbon dioxide (CO<sub>2</sub>) with hydrogen (H<sub>2</sub>) to produce carbon monoxide (CO), reduction of  
30 carbon dioxide (CO<sub>2</sub>) with hydrogen (H<sub>2</sub>) to produce methanol (CH<sub>3</sub>OH) and higher alcohols. In the case of nitric oxide (NO), the microwave plasma apparatus enables direct conversion of nitrogen and oxygen to nitric oxide (NO) at temperatures and pressures which are easier to achieve.

In short, the technique requires significantly lower temperatures and pressures than those commonly required for the production of ammonia, nitric oxide and fuels derived from methane.

- 5 Preferably, at least some of the method steps are performed at a pressure greater than 103,421 Pa (15 psi).

The step of directing a plurality of reagents into contact with the catalyst may involve passing at least one of the reagents via the multimodal microwave cavity.

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The step of directing a plurality of reagents into contact with the catalyst may involve passing at least one of the reagents directly into contact with the catalyst, bypassing the multimodal microwave cavity.

- 15 Preferably, the method further comprises spreading the plasma prior to directing the plasma into contact with the catalyst.

Preferably, spreading of the plasma involves use of a perforated plate.

- 20 Preferably, the plasma is generated using microwave radiation from a first microwave radiation source.

Preferably, there may be microwave radiation provided to the catalyst that may be generated using a second microwave radiation source, different from the first microwave radiation source.

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Preferably, the frequency of the microwave radiation used to generate the plasma is either 2.45 GHz or 896 MHz.

- 30 In a second aspect of the invention, there is provided an apparatus for facilitating a chemical reaction, the apparatus comprising:

a plasma source; a reagent supply assembly; and a catalytic reaction chamber for accommodation of one or more catalysts,

- 35 wherein the reagent supply assembly is arranged to facilitate the supply of reagent directly or indirectly into the catalytic reaction chamber and wherein the reagent supply

assembly comprises a plurality of reagent inlets, each connectable to a supply of reagent, wherein each reagent inlet comprises a flow controller;

wherein the plasma source comprises: a plasma source gas inlet; a plasma confinement vessel downstream of the plasma source gas inlet; a microwave chamber  
5 which surrounds at least a part of the plasma confinement vessel; a first microwave source for supplying microwave radiation to the microwave chamber; and a plasma source outlet downstream of the plasma confinement vessel and in fluid communication with the catalytic reaction chamber, wherein the plasma source is configured so as to establish a non-resonant multi-mode microwave cavity in the microwave chamber and the plasma  
10 confinement vessel;

wherein the plasma source gas inlet is configured to influence the direction of flow of a received supply of gas so as to introduce the gas into the plasma confinement vessel as a vorticular or swirled flow;

wherein the catalytic reaction chamber comprises a catalytic reaction chamber  
15 outlet for a product produced in the catalytic reaction chamber; and

wherein the plasma confinement vessel is configured:

- (a) to receive plasma initiating gas from the plasma source gas inlet; and
- (b) to contain gas and a plasma once initiated.

20 The reagent supply assembly may be arranged to facilitate the supply of reagent:

- (a) upstream of the plasma source; or
- (b) downstream of the plasma source and upstream of the catalytic reaction chamber; or
- (c) so as to enter directly into the catalytic reaction chamber.

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Preferably, the apparatus comprises a first pressure controller located downstream of the reagent supply assembly and a second pressure controller located downstream of the catalytic reaction chamber.

30 Preferably, the apparatus comprises a spreader between the plasma source and the catalytic reaction chamber. The spreader, where present, may comprise a perforated plate.

The apparatus may comprise a second microwave radiation source, different from the first  
35 microwave radiation source, the second microwave radiation source configured to provide microwave radiation to the catalytic reaction chamber.

Preferably, the first and/or the second microwave radiation source is configured to provide microwave radiation at a frequency of either 2.45 GHz or 896 MHz.

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### **Brief description of the drawings**

Figure 1 shows a first embodiment of an apparatus in accordance with the present disclosure;

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Figure 2 shows a second embodiment of an apparatus in accordance with the present disclosure;

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Figure 3 shows a microwave plasma generator for use in method and apparatus of the present disclosure; and

Figure 4 shows plan view of the microwave plasma generator of Figure 3.

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### **Detailed description**

A first embodiment of an apparatus in accordance with the present disclosure is shown in Figure 1.

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The apparatus 1 comprises a plasma source 10, a catalytic reaction chamber 20 and at least one reagent gas supply assembly 30, 40. The plasma source 10 is configured to supply plasma to the catalytic reaction chamber 20. The one or more reagent gas supply assemblies 30, 40 are configured to supply reagent gases directly or indirectly to the catalytic reaction chamber 20.

30

The plasma source 10, which is illustrated in more detail in Figures 3 and 4, comprises a microwave chamber 50 which is coupled to a first microwave source 51 via a waveguide 52. The plasma source 10 further comprises a plasma confinement vessel 15 which is partly surrounded by the microwave chamber 50. A first, upper part of the plasma confinement vessel 15a which is surrounded by the microwave chamber 50 is preferably

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formed from a refractory material such as quartz. A second, lower part of the plasma

confinement vessel 15b which is not surrounded by the microwave chamber 50 is preferably formed from a metal such as aluminium. At the upper end of the plasma confinement vessel 15, as seen in Figure 1, is a plasma confinement vessel gas inlet 12 which is in fluid communication with the gas inlet 2 of the gas treatment device 1. The plasma source gas inlet 2 includes a pressure controller 37a and a flow controller 37b. The plasma source 10 further comprises a plasma source outlet 17.

The terms "upper" and "lower" are used simply to describe the relative position of the parts of the tube in the illustrated embodiment. The apparatus could be orientated differently, for example, horizontally or upside down. Thus, the relative terms "upper" and "lower" are to be understood in this context.

The plasma confinement vessel gas inlet 12, which is illustrated in more detail in Figures 3 and 4, includes, in this example, two conduits 121, 122 and a curved section passage 14 in communication with the plasma confinement vessel gas inlet 12. The two conduits 121, 122 have a longitudinal axis which is substantially tangential to a curved inner surface of the curved section passage 14.

The curved section passage 14 has a longitudinal axis. The longitudinal axes of each of the two conduits 121, 122 each intersect a plane orthogonal to the longitudinal axis of the passage 14 at an angle of between about 0° and 30°.

This plasma confinement vessel gas inlet 12 is shown in plan view in Figure 4 and contains a central, generally cylindrical bore 14. As seen from Figure 4, this cylindrical bore 14 is coaxial with the longitudinal bore of the plasma confinement vessel 15, and the plasma source outlet 17. In preference, the diameter of the central bore 14 of plasma confinement vessel gas inlet 12 is slightly larger than the diameter of the plasma confinement vessel 15.

The plasma source 10 further comprises a starting device 11. In the preferred embodiment, the starting device 11 is an electric ignition device 11 that is located at the top of the plasma confinement vessel 15. The electric ignition device 11 may be an electrode energised by a Tesla coil. A second electrode may simply be a metal portion of the plasma confinement vessel 15.

In an alternative embodiment, the starting device may be a graphite lighting rod, which may be inserted through an aperture located midway along the length of the confinement vessel.

5 The diameter of the microwave chamber 50 is preferably around 16 cm, and the microwave chamber 50 is also around 16 cm in length. The microwave source 51 is, in preference, capable of producing a range of power outputs and frequencies up to 5 kW and 2.45 GHz respectively. For a microwave chamber 50 having a diameter of approximately 16 cm, and height of approximately 16 cm, a frequency of 2.45 GHz is preferred in order that the  
10 chamber behaves as a non-resonant multi-mode microwave cavity. Another common microwave frequency is 896 MHz. Since this frequency involves a proportionally larger microwave wavelength, this requires a proportionally larger chamber in order to behave as a non-resonant multi-mode microwave cavity. In short, a different size of microwave chamber 50 will require a different frequency in order to establish the required non-  
15 resonant, multi-mode cavity.

Whilst a continuous microwave source is envisaged in the following, it is to be understood that a pulsed microwave source is equally feasible.

20 The plasma source outlet 17 is in fluid communication with the catalytic reaction chamber 20. As such, in operation, plasma exiting the plasma source outlet 17 flows into the catalytic reaction chamber 20 via a catalytic reaction chamber aperture. In the illustrated embodiment, the plasma source outlet 17 and the catalytic reaction chamber aperture are, in effect, one and the same aperture. However, in an alternative embodiment the plasma  
25 source outlet 17 may be separate from the catalytic reaction chamber aperture, perhaps connected by a conduit.

The catalytic reaction chamber 20 comprises, in addition to a catalytic reaction chamber aperture, a catalytic reaction chamber outlet 23.

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A perforated plate (not shown) is located proximate the catalytic reaction chamber aperture. The purpose of the perforated plate is: to spread the plasma evenly within the catalytic reaction chamber 20; to avoid "hot-spots" within the catalytic reaction chamber 20 that are receiving a large proportion of the plasma; and also to seek to maintain the  
35 vorticular or swirled flow of plasma present in the plasma confinement vessel 15 into the catalytic reaction chamber 20. Alternative means than a perforated plate but which

achieves the same functionality falls within the scope of the disclosure. For example, it may be that the aperture is itself shaped in such a way as to achieve an even flow of plasma within the catalytic reaction chamber 20.

5 The catalytic reaction chamber outlet 23 is in fluid communication with the gas outlet 3.

The catalytic reaction chamber 20, at least when in use, includes one or more catalysts 25, either as a coating to the catalytic reaction chamber itself and/or as one or more separate materials placed in an appropriate part of the catalytic reaction chamber 20. The catalytic  
10 reaction chamber 20 may further comprise one or more supports for supporting the one or more catalysts 25. The one or more supports may themselves behave as catalysts 25.

Alternatively, the catalysts may be incorporated into the chamber and/or the supports and/or any other carrier by a range of methods including but not limited to deposition  
15 including CVD (chemical vapour deposition), sputtering, spray coating and wash-coating.

The nature and production of the catalysts are discussed in more detail below.

There may be one or more than one reagent gas supply assembly 30, 40. In the illustrated  
20 embodiment of Figures 1 and 2, there are two reagent gas supply assemblies 30.

The first reagent gas supply assembly 30 comprises one or more reagent inlets 31, 32, 33 for supply of reagent. Each of the one or more reagent inlets 31, 32, 33 may comprise a pressure controller 34a, 35a, 36a and a flow controller 34b, 35b, 36b. Where there is more  
25 than one reagent inlet 31, 32, 33, they may combine into a single reagent supply line 38. The reagent supply line 38 is in fluid communication with an upstream end of the plasma confinement vessel 15 and feeds into the plasma confinement vessel gas inlet 12. The flow controllers 34b, 35b, 36b may be mass flow controllers, rotor flow controllers, rotor meters, valves or any other flow controllers.

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The second reagent gas supply assembly 40 comprises one or more reagent inlets 41, 42, 43 for supply of reagent. Each of the one or more reagent inlets 41, 42, 43 may comprise a pressure controller 44a, 45a, 46a and a flow controller 44b, 45b, 46b. Where there is more  
than one reagent inlet 41, 42, 43, they may combine into a single reagent supply line 48.

35 The reagent supply line 48 is in fluid communication with an upstream end of the catalytic

reaction chamber 20. The flow controllers 44b, 45b, 46b may be mass flow controllers, rotor flow controllers, rotor meters, valves or any other flow controllers.

5 It is not essential for there to be more than one reagent gas supply assembly. If there is only one reagent gas supply assembly, it may be located either in fluid communication with an upstream end of the plasma confinement vessel 15 (as in the case of illustrated reagent gas supply assembly 30) or in fluid communication with an upstream end of the catalytic reaction chamber 20 (as in the case of illustrated reagent gas supply assembly 40).

10 In operation, a plasma source gas is received into the gas inlet 2 and passes into the plasma confinement vessel 15 via the plasma confinement vessel gas inlet 12 having the two opposed conduits 121, 122. These conduits 121, 122 open into the central bore 14 of the gas inlet member 12 at a tangent as best seen in Figure 4. The longitudinal axes of the conduits 121, 122 are also canted downwards at an angle of around  $15^\circ$  to the longitudinal axis of the microwave chamber 50 and the plasma confinement vessel 15 in particular.

Hence, the plasma initiating gas is fed into the cylindrical bore 14 tangentially and, as such, it is wrapped around in a generally circular direction so that the gas as injected into the plasma confinement vessel 15 is likewise swirling around. The downward cant of the inlets 20 121, 122 introduces a downward component to the flow of the plasma gas so that the resultant gas flow into the plasma confinement vessel 15 is in the form of a vortex.

By "downward" it is simply meant that the gas flows towards the exit. In the typical arrangement, this is vertically below the inlet, but it is to be understood that the device may 25 be operated at any arbitrary orientation. Thus, the chamber may, for example, be mounted upside down, or horizontally, so that the inlet is then, strictly, above the exit or horizontally in line with it, respectively. The word "downward" is thus to be understood in this context.

This vorticular flow of plasma gas prevents the first part of the plasma confinement vessel 30 15a from overheating, particularly at low flow rates; overheating leads to the first part of the plasma confinement vessel 15a becoming absorbent to microwave energy which in turn leads to thermal runaway. It will be understood from the foregoing, however, that the vorticular flow provides an additional advantage of stability which permits relatively high flow rates.

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In operation, a small amount of plasma-forming gas is first of all introduced into the plasma confinement vessel 15 via the plasma confinement vessel gas inlet 12. The microwave source 51 is then activated and the electric ignition device 11 is used to generate a spark in the plasma confinement vessel 15 in order to initiate a plasma. A microwave field generated by the microwave source 51 causes a microwave field to propagate not only in the microwave chamber 50 and the first, upper part of the plasma confinement vessel 15a which the microwave chamber 50 surrounds, but also in the second, lower part of the plasma confinement vessel 15b. The second part of the plasma confinement vessel 15b being made of metal allows the microwave field to be contained therein. The flow rate of the plasma gas is then typically increased, and a body of plasma 100 is established which, at its broadest point, fills the confinement vessel 15.

Once the plasma has been struck, it is sustained by the collision of electrons that have been accelerated by the microwave field with the other (larger) species present (and with each other), leading to raised temperatures. The diffuse, glowing plasma 100 is homogeneous and its shape can be changed according to the plasma confinement vessel 15.

Other methods of starting the plasma could, of course, be contemplated. These include, but are not limited to, employing a reduced pressure (around 30 mbar) at which pressure spontaneous ignition occurs, or, as mentioned previously, using a graphite lightning rod that may be temporarily inserted into the plasma confinement vessel 15.

The stability, size and shape of the body of plasma 100, as well as the dimensions of the plasma exiting through the outlet 17 of the plasma source (all of which are a result of a variety of factors as explained above) are controlled by the power of the microwave source 51 and the flow rate of the plasma gas.

Once plasma is established, one or more reagent gases are supplied so as to enter the catalytic reaction chamber 20 via the reagent supply line or lines 38, 48. Preferably, each reagent gas enters via its own reagent inlet 31, 32, 33, 41, 42, 43. With each reagent inlet 31, 32, 33, 41, 42, 43 having its own associated flow controller 34b, 35b, 36b, 44b, 45b, 46b such that supply of each reagent gas can be independently controlled.

As mentioned previously, it is not essential for there to be more than one reagent gas supply assembly. If there is only one reagent gas supply assembly, it may be located

either in fluid communication with an upstream end of the plasma confinement vessel 15 or in fluid communication with a downstream end of the plasma confinement vessel 15 and an upstream end of the catalytic reaction chamber 20.

5 As would be well understood by the skilled person, the number of reagent inlets is not limited to that of the illustrated embodiment. There may be any number of reagent inlets. In a specific installation intended for a specific reaction, the number of reagent inlets may be exactly as required for the specific reaction. In an apparatus not intended for a specific  
10 flexibility to allow for reactions which may require a large number of reagents.

For some reactions, it may be appropriate that one or more of the reagent gases is supplied upstream of the plasma confinement vessel 15 while another one or more of the reagent gases is supplied downstream of the plasma confinement vessel 15. For example,  
15 some gases, such as CO<sub>2</sub>, N<sub>2</sub> and O<sub>2</sub>, may be supplied upstream of the plasma confinement vessel 15 whereas other gases, such as CH<sub>4</sub>, may be supplied downstream of the plasma confinement vessel 15 in order to avoid the CH<sub>4</sub> undergoing undesired reactions.

20 While, in the illustrated embodiment, the reagent gases supplied upstream of the plasma confinement vessel 15 feed into the plasma confinement vessel gas inlet 12, it is possible instead (or in addition) to have the reagent gases supplied upstream of the plasma confinement vessel 15 feed into the plasma confinement vessel 15 at an alternative inlet that does not give rise a vorticular or swirled flow.

25 The presence of plasma in the catalytic reaction chamber 20 causes the one or more catalysts 25 therein to be activated in order to react with the reagent gases that have been received into the catalytic reaction chamber via any of the routes previously described. Activation of the one or more catalysts by the plasma involves the generation of highly  
30 reactive gas phase free radicals such as O<sup>•</sup>, OH<sup>•</sup>, H<sup>•</sup> which react with the reagent gases in the catalyst reaction chamber to effect the desired chemical conversion.

Plasma increases the reaction efficiency since electrons and ionized molecules produced by the microwave plasma from N<sub>2</sub>, CO<sub>2</sub>, O<sub>2</sub>, H<sub>2</sub>O and volatile organic compounds can  
35 collide with other molecules in the gas stream, leading to their activation through their vibrational excitation but also providing routes to dissociation or ionization. The molecules

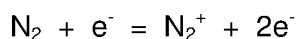
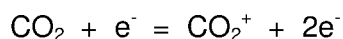
are absorbed onto the surface of the catalyst where they are brought together and react. The products of the reaction may be inert materials which are released from the surface of the catalyst which regenerates the catalyst. The result is an increase in reactivity.

5 The reagent activation by electron impact or by reactions with atomic and molecular active species occurs in the plasma. These may be charged ionic species or radical species. Moreover, energized electrons may generate a number of other short living active species, e.g. excited molecules or radicals at higher electron or vibrational states.

10 Examples of reactive species that may be generated in plasma, dependent on the reagents used, include the following:



15  $\text{H}_2\text{O} + e^- = \text{H}_2\text{O}^+ + 2e^-$



Molecules in high energy states can be produced by collisions of, for example,  $\text{CO}_2^+$ ,  $\text{H}_2\text{O}^+$ , and  $\text{N}_2^+$ .

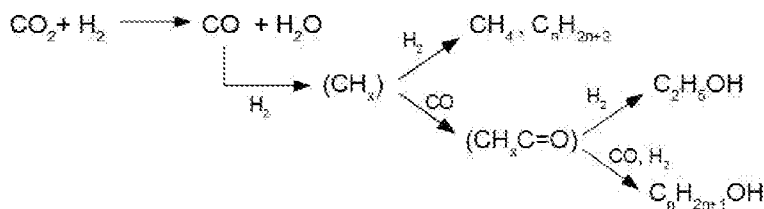
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By enabling the efficient production of reactive species such as those examples given above, subsequent chemical reactions involving such species can be achieved with lower energy input. This is because the activation energy to achieve conversion to the desired end products is reduced by virtue of the reactive species already present in the plasma.

25 Overall, this means that the total energy required to produce the end product may be much lower than that required using conventional techniques.

The reaction scheme below illustrates some example reactions that are possible using the method and apparatus of the present disclosure.

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Gases that are products of the reactions that take place in the catalytic reaction chamber 20 may pass out of the catalytic reaction chamber 20 via the catalytic reaction chamber outlet 23. An outlet pressure controller 27 is located in proximity to the catalytic reaction chamber outlet 23. The inlet pressure controller(s) 34a, 35a, 36a, 37a, 44a, 45a, 46a and the outlet pressure controller 27 may be controlled so as to maintain a particular pressure in the catalytic reaction chamber 20 appropriate for maintaining the desired reactions.

Figure 2 shows a further embodiment of a gas treatment device 1 according to the disclosure. This is identical to the embodiment of Figure 1, except that it also includes a second microwave source 60 located to emit microwave radiation directly towards the catalytic reaction chamber 20 in order to provide more energy and thereby to assist in the chemical reactions. Again, the same variations with respect, for example, to the reagent gas supply assembly or assemblies 30, 40 may be equally applicable to the Figure 2 embodiment as the Figure 1 embodiment.

The plasma has been shown to be essentially non-equilibrium in nature, and it therefore produces a rich stream of activated species that can greatly increase the rate of normal catalytic processes.

## **20 Catalysts**

The one or more catalysts 25 may be based on and/or supported by porous or non-porous plates, honeycombs, foams and granular materials. They can be permeable or non-permeable, usually, but not limited to, ceramics. The one or more catalysts 25 can be monolithic, or coated on a monolithic support, or applied as a coating to other articles such as beads or pellets.

The one or more supported or monolithic catalysts 25 may be classified into different groups depending on the types of chemical reaction for which they are active.

The most common examples of heterogeneous catalysis in industry involve the reactions of gases being passed over the surface of a solid, often a metal, a metal oxide or a zeolite. The plasma reaction system can, in principle, be used with a number of different types of catalyst and is not limited by type. The catalyst can be chosen for the desired chemical process depending upon the reactants involved in the chemical process and the desired transformation. Examples include Iron based catalysts for ammonia synthesis, Nickel for

synthesis gas, zeolites for catalytic cracking of gas oil, Platinum and Rhenium on alumina for reforming of naphtha, Vanadium (V) oxide on silica for sulphuric acid and Platinum and Rhodium for nitric acid synthesis.

- 5 The catalysts may be tailored for plasma activation by selection of the catalyst material and its porosity. Materials that improve catalyst activity and the method of incorporation/accommodation of the catalyst in the catalytic reaction chamber can be incorporated. Furthermore, in embodiments where the chamber includes one or more supports for accommodation of the one or more catalysts 25, the nature and porosity of the
- 10 one or more supports are selected to improve catalyst activity. The one or more catalysts may be coated onto substrates having a surface structure and porosity selected to maximise catalyst activity in the chamber.

- The one or more catalysts 25 may be based on porous ceramic materials coated with
- 15 active catalytic substances. The catalyst can be any catalytically active substance which may be supported on a porous substrate, or is a metal/metal alloy or is a zeolite or modified zeolite, for example.

**CLAIMS:**

1. A method of facilitating a chemical reaction, the method comprising:  
generating a plasma by introducing a plasma source gas as a vorticular or swirled  
5 flow into microwave radiation contained in a non-resonant multimodal microwave cavity;  
directing the plasma into contact with a catalyst;  
directing a plurality of reagents into contact with the catalyst; and  
performing at least some of the method steps at a pressure greater than  
atmospheric pressure (101,325 Pa),  
10 wherein the method comprises controlling a flow of each of the plurality of reagents  
independently.
2. The method of claim 1 wherein at least some of the method steps are performed at  
a pressure greater than 103,421 Pa (15 psi).  
15
3. The method of claim 1 or claim 2 wherein the step of directing a plurality of reagents  
into contact with the catalyst involves passing at least one of the reagents via the  
multimodal microwave cavity.
- 20 4. The method of any preceding claim wherein the step of directing a plurality of  
reagents into contact with the catalyst involves passing at least one of the reagents directly  
into contact with the catalyst, bypassing the multimodal microwave cavity.
5. The method of any preceding claim and further comprising spreading the plasma  
25 prior to directing the plasma into contact with the catalyst.
6. The method of claim 5 wherein the step of spreading the plasma involves use of a  
perforated plate.
- 30 7. The method of claim 5 wherein the step of spreading the plasma involve use of an  
aperture configured to effect spreading of the plasma.
8. The method of any preceding claim wherein the plasma is generated using  
microwave radiation from a first microwave radiation source.

9. The method of any preceding claim further comprising providing microwave radiation to the catalyst.

10. The method of claim 9 wherein the microwave radiation provided to the catalyst is generated using a second microwave radiation source, different from the first microwave radiation source.

11. The method of any preceding claim wherein the frequency of the microwave radiation used to generate the plasma is either 2.45 GHz or 896 MHz.

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12. An apparatus for facilitating a chemical reaction, the apparatus comprising:  
a plasma source; a reagent supply assembly; and a catalytic reaction chamber for accommodation of one or more catalysts,

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wherein the reagent supply assembly is arranged to facilitate the supply of reagent directly or indirectly into the catalytic reaction chamber and wherein the reagent supply assembly comprises a plurality of reagent inlets, each connectable to a supply of reagent, wherein each reagent inlet comprises a flow controller;

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wherein the plasma source comprises: a plasma source gas inlet; a plasma confinement vessel downstream of the plasma source gas inlet; a microwave chamber which surrounds at least a part of the plasma confinement vessel; a first microwave source for supplying microwave radiation to the microwave chamber; and a plasma source outlet downstream of the plasma confinement vessel and in fluid communication with the catalytic reaction chamber, wherein the plasma source is configured so as to establish a non-resonant multi-mode microwave cavity in the microwave chamber and the plasma confinement vessel;

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wherein the plasma source gas inlet is configured to influence the direction of flow of a received supply of gas so as to introduce the gas into the plasma confinement vessel as a vorticular or swirled flow;

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wherein the catalytic reaction chamber comprises a catalytic reaction chamber outlet for a product produced in the catalytic reaction chamber; and

wherein the plasma confinement vessel is configured:

(a) to receive plasma initiating gas from the plasma source gas inlet; and

(b) to contain gas and a plasma once initiated.

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13. The apparatus of claim 12 wherein the reagent supply assembly is arranged to facilitate the supply of reagent:

- (a) upstream of the plasma source; or
- (b) downstream of the plasma source and upstream of the catalytic reaction chamber; or
- (c) so as to enter directly into the catalytic reaction chamber.

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14. The apparatus of claim 12 or claim 13 and further comprising a first pressure controller located downstream of the reagent supply assembly and a second pressure controller located downstream of the catalytic reaction chamber.

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15. The apparatus of any of claims 12 to 14 and further comprising a spreader between the plasma source and the catalytic reaction chamber.

16. The apparatus of claim 15 wherein the spreader comprises a perforated plate.

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17. The apparatus of claim 15 wherein the spreader comprises an aperture configured to effect spreading of the plasma.

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18. The apparatus of any of claims 12 to 17 and further comprising a second microwave radiation source, different from the first microwave radiation source, the second microwave radiation source configured to provide microwave radiation to the catalytic reaction chamber.

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19. The apparatus of any of claims 12 to 18 wherein the first and/or the second microwave radiation source is configured to provide microwave radiation at a frequency of either 2.45 GHz or 896 MHz.

20. An apparatus as hereinbefore described and with reference to the accompanying drawings.

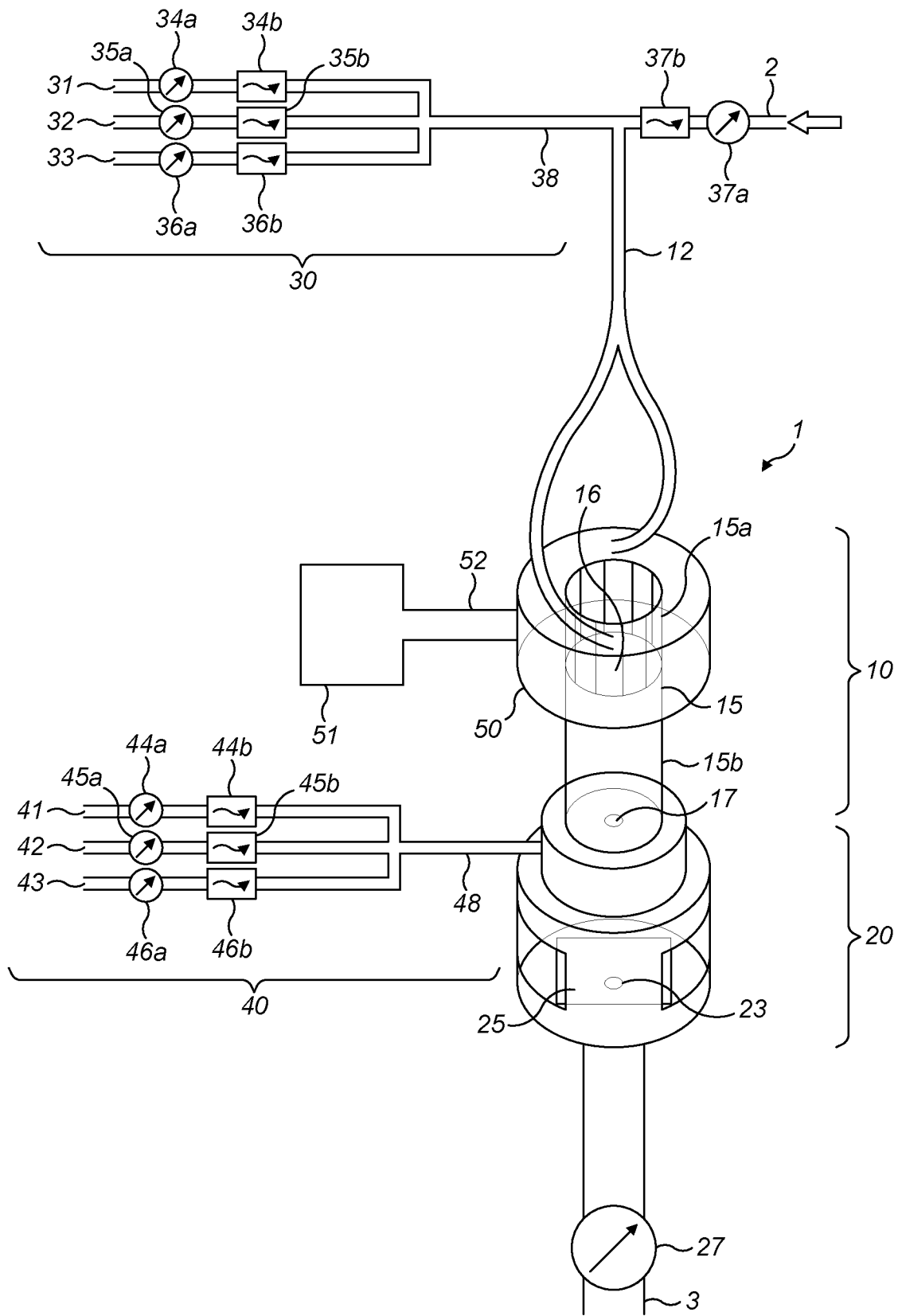


FIG. 1

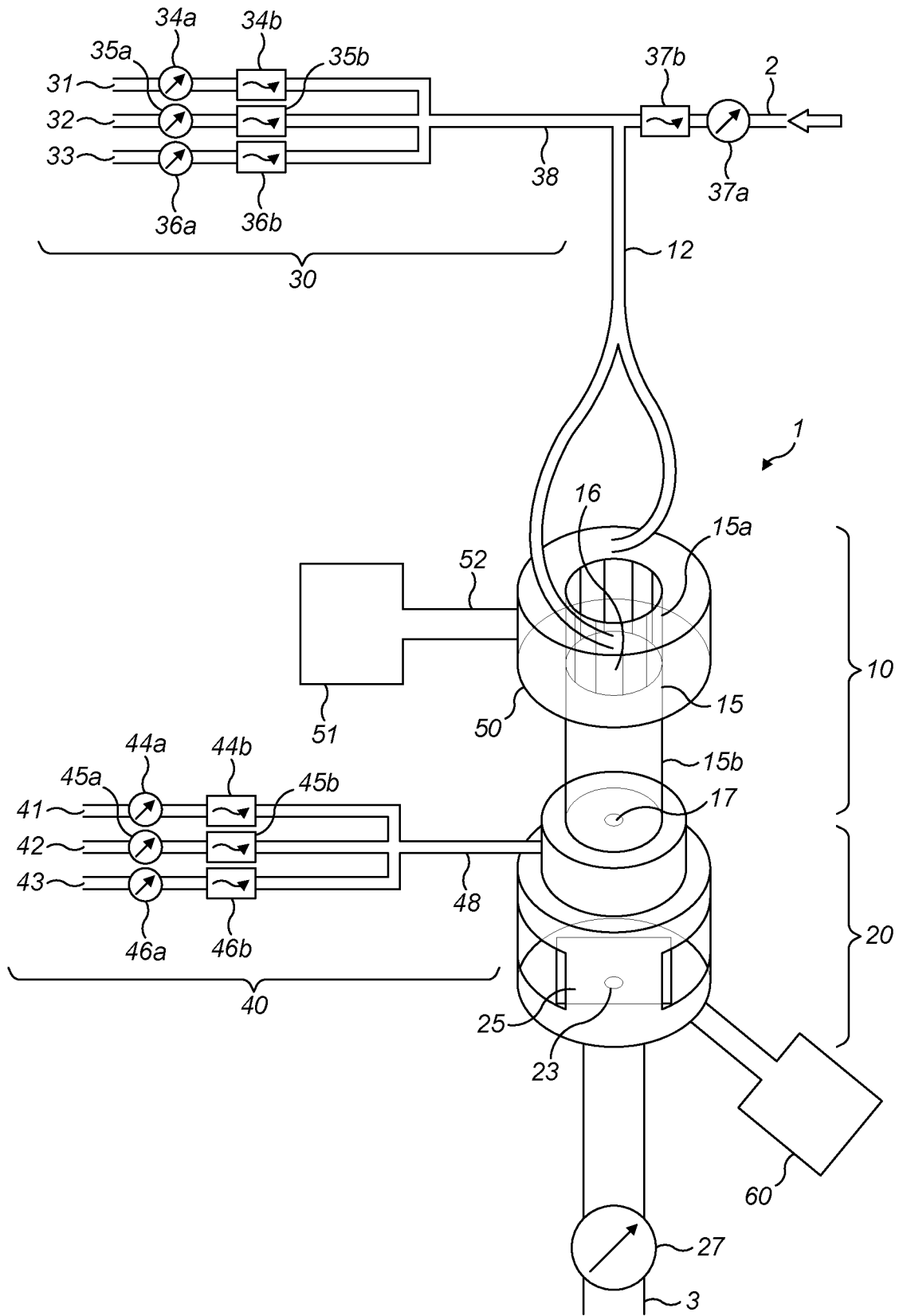


FIG. 2

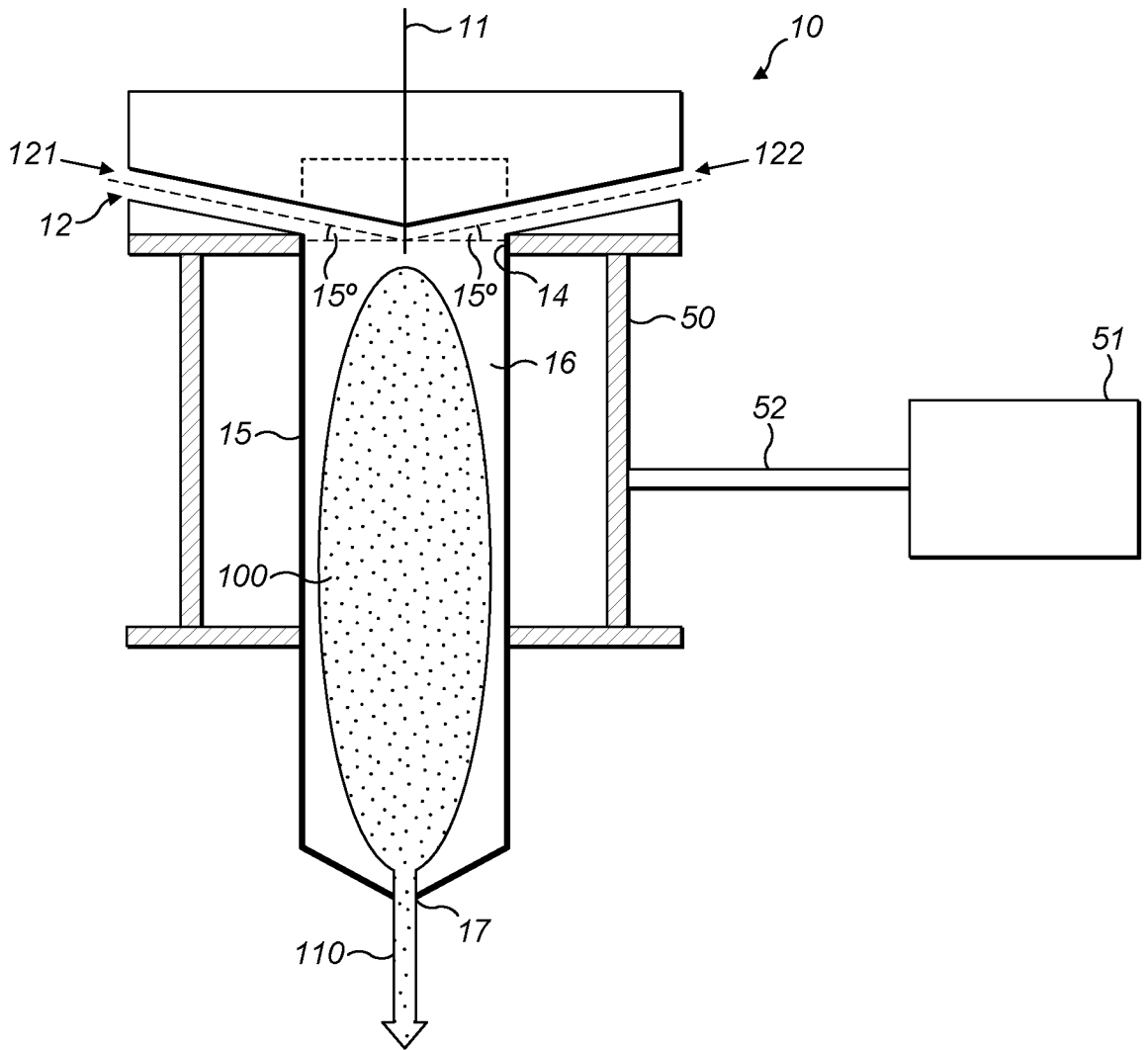


FIG. 3

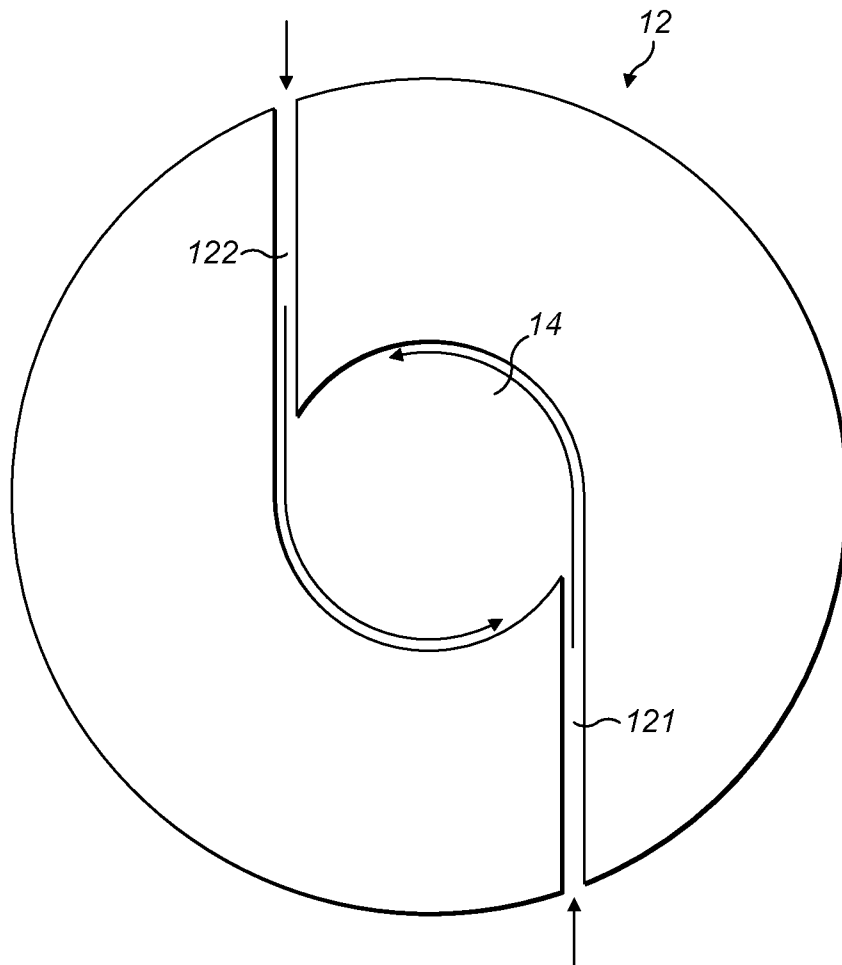


FIG. 4